Defense Technical Information Center
Compilation Part Notice

ADP010483

TITLE: An Integrated Process for Design and
Validation of Flight Control Laws of Flexible
Aircraft Structure

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Structural Aspects of Flexible Aircraft
Control [les Aspects structuraux du controle
actif et flexible des aeronefs]

To order the complete compilation report, use: ADA388195

The component part is provided here to allow users access to individually authored sections
of proceedings, annals, symposia, ect. However, the component should be considered within
the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP010474 thru ADP010498

AN INTEGRATED PROCESS FOR DESIGN AND VALIDATION OF FLIGHT CONTROL LAWS OF FLEXIBLE AIRCRAFT STRUCTURE

Michel Lacabanne, Marc Humbert

Aerospatiale Matra Airbus
316 route de Bayonne, 31060 Toulouse, France

Abstract

This paper recalls some problems which need to be carefully studied in relation with flexibility of large transport aircraft and control laws design. The evolution of flexible aircraft models is described, and it is shown that the evolution of the FCS design process is coming along with more interdisciplinary models. The FCS validation process is supported by models, and by flight tests. The need to perform an in flight identification of structural modes is explained, as well as the methodology which could be used for future very large transport aircraft.

Introduction

Electronic Flight Control Systems (EFCS) have been implemented on AIRBUS subsonic civil aircraft since A320. The Airbus family has grown, mainly with derivatives of A320, and also with long range twin and four engine aircraft. From this date, EFCS have been embodied on all Airbus types civil transport aircraft. The increasing size of aircraft has emphasized the effects of structural flexibility on general aircraft performance. The evolution of aircraft features in combination with the implementation of EFCS is leading to promote interdisciplinary ways of working and to develop new tools, wherever necessary, in order to better predict the overall aircraft performance and to obtain the best achievable design.

This paper shows that the evolution of the FCS design and validation process strongly depends on the progress made with the flexible aircraft models. The flexible aircraft models upgrade the flight mechanics models, and, according the assumptions made, they can be used for FCS design or validation. The use of such models helped FCS designers to implement active control of flexible modes. For this reason, if high performance of the controller is looked for, progress will have to be made in order to achieve an in flight identification of structural and flight mechanics modes consistent with the performance level which is aimed.

List of notations

$[M]$ $[B]$ $[K]$ Mass, damping and stiffness matrices

$[\mu]$ $[\beta]$ $[\gamma]$ Generalized Mass, damping and stiffness matrices

$[\phi]$ modal displacement matrix

$\{X\}$ structure displacement vector, or state vector

$\{q\}$ generalized coordinated vector

$[GAF]$ Generalized aerodynamic forces matrix

$[GAF_\delta]$ Generalized aerodynamic forces matrix associated with control surface rotation

δ control surface rotation

$\{U\}$ input vector (control surface rotation...)

$\{Y\}$ output vector (sensor accelerations, speed...)

$[A]$, $[B]$, $[C]$, $[D]$ state space model matrices

Typical FCS design problems in relation with structural flexibility

A large number of problems need to be solved during FCS design. Some of them are directly linked with the aircraft structural flexibility. Three typical FCS design problems are briefly reminded below:

- **Interaction of Control, with Aerodynamic and Structure (ICAS)**

The FCS designers must be careful in order to avoid the Interaction of Control, with Aerodynamic and Structure in the whole flight domain, for all mass configurations, slats and flaps configurations.

Indeed, the direct consequence of ICAS is the modification of "in flight" structural modes damping. A damping decrease of some structural modes can be observed.
ICAS should not give zero damping for any of the structural mode and a sufficient stability margin should exist. While flutter of modern civil transport aircraft, which is due to Interaction of Aerodynamic and Structure is likely to happen at high speeds in the transonic regime, on contrary ICAS, can occur at low speeds and Mach numbers according to the FCS tuning (gain and phase values).

- **Oscillatory Failure Loads (OFL)**

The oscillatory failures on control surfaces are another important concern. In some failure cases (for example, actuator bad functioning or control laws failure), the FCS do not operate properly.

The Control surfaces can oscillate at a fixed frequency and produce high structural loads, except if special care is taken during structural and FCS design (for example, monitoring the oscillations which would impair structural integrity, then switch FCS to a safe configuration).

- **Aircraft Pilot Coupling (APC)**

The Aircraft Pilot Coupling, which is the coupling of the pilot with Aircraft structural modes through the FCS, is not acceptable for handling.
APC can generally be prevented thanks to appropriate filtering in the feed forward path.

Evolution of Flexible aircraft modelizations: from the flutter equations to the integral model

The history of aeronautical progress demonstrated that new technologies have always pushed the need for new models; the aeroelasticity field is a clear example of this link. Aeroelastic models have deeply evolved recently to handle the new issues raised by very flexible, new large transport aircraft, and the integration of digital technology into the flight control system. This kind of evolution of the aeroelastic models developed by AM-Airbus for Airbus programs development and certification is described below.

- **The flutter equation in the frequency domain and its improvement to cope with the electronic flight control system apparition**

The first historical model of the flexible aircraft consists in the flutter equations expressed in the frequency domain. This model is built from a structural model and an aerodynamic model linked together to describe coupling between structural and aerodynamic forces. It is commonly written in the normal modal basis, driving the following well-known equation:

$$-\varpi^2 [\mu]\{q\} + (j\varpi)[\beta]\{q\} + [\gamma]\{q\} = \bar{q}.[GAF]\{q\} \quad (1)$$

The fact that this equation is named "the flutter equation" may lead to think that all of the aeroelastic science lies in this single equation. One has to admit that this statement is not so false. This model is dedicated to analysis of the stability of the structural forces – aerodynamic forces coupling that is still the first concern of aeroelasticians, and is therefore still widely used today. Moreover, this historical model is still living, and has known many evolutions to integrate the best structural and aerodynamic data available, from the first finite element models in structure and aerodynamics, to today's last unsteady aerodynamic transonic codes.
However, today's flexible aircraft challenges can not be addressed using this only model.
The first evolution of it was driven by the EFCS integration that requires pushing forward this stability model into an input – output model. A flexible aircraft model describing the dynamics between control surfaces movements to control law sensors was required and derived by adding few terms to model (1):

$$\left.\begin{array}{l} -\varpi^2 [\mu]\{q\} + (j\varpi)[\beta]\{\dot{q}\} + [\gamma]\{q\} = \\[2mm] ...\bar{q}.[GAF]\{q\} + \bar{q}.[GAF_\delta].\{\delta\} \\[2mm] \{Y\} = [\phi].\{q\} \ or \ (j\varpi).[\phi].\{q\} \ or \ -\varpi^2.[\phi]\{q\} \end{array}\right\} \quad (2)$$

The aeroelasticians were then able to analyse EFCS effects on flexible mode stability by introducing a control law model in a linearized form, in the frequency domain, into the model (2):

$$\{\delta\} = H(j\varpi).[Y]$$

- **The time domain approximation of unsteady aerodynamic forces; the aeroelastic model in the state space form and its derivatives**

Because the unsteady aerodynamic forces are easily computed in the frequency domain only, the previous models are limited to the frequency domain only. This barrier was broken in the 70's by the proposal of a time domain approximation of the unsteady aerodynamic forces:

$$[GAF(M,\varpi/V)] \approx [gaf(M,p)] \quad p = j.\varpi$$

Where

$$[GAF(M,\varpi/V)] \text{ , } p \text{ rational approximation of the}$$
$$GAF \text{ matrix}$$

Two methods are offered to carry this approximation; the Roger's approximation or the minimum state method (Ref 1 and 2). Using one of these, the model (2) can be turned into a time domain model. These approximations open the aeroelasticians to some of the special features of the time domain simulations: comparisons between flight test and model time histories, analyses of some non-linearities (structure, control system...).

Moreover, the time domain aeroelastic model can then be easily expressed in the state space form:

$$\left.\begin{array}{l} \{\dot{X}\}=[A]\{X\}+[B]\{U\} \\ \{Y\}=[C]\{X\}+[D]\{U\} \end{array}\right\} \quad (3)$$

The state space form may be regarded as a standard of dynamic system modelization, around which a large number tools have been developed by the automaticians community for analyses, simulation, reduction, and control.

The state space formulation was a really strong evolution in flexible aircraft modelization. Thanks to its well known form, it created the basis for an interdisciplinary modelization of the flexible aircraft, and an efficient communication tool between aeroelasticians and specialists from other fields (flight mechanics, control law design, simulation...), who became involved in the structural dynamics issues.

The first example of interdisciplinary modelization around the flexible aircraft was the introduction of some flight mechanics behaviour informations into the state space aeroelastic model (3). This was achieved and used in AM-Airbus following two axes: The first one consists in taking into the normal modal basis of (3) the rigid body modes. This approach is commonly used for dynamic loads computation. Using the same formulation of (3), the model is now extended by some flight mechanics representation; when doing so, care must be taken to insure community with already existing flight mechanics models. A second approach consists in putting the aeroelastic model (3) together with a flight mechanics model also derived in the state space form, by simply adding the outputs of both models.

Approach 1:
Model (3) with $[\phi] = [\phi_{rigid} \quad \phi_{flexible}] \Rightarrow \{X\} = \left\{\begin{array}{l} X_{rigid} \\ X_{flexible} \end{array}\right\}$

Approach 2:
Model (3) together wit flight mechanics state space model

$$\left.\begin{array}{l} \\ \\ \\ \\ \\ \\ \\ \end{array}\right\}(4)$$

• **Coming to an interdisciplinary flexible aircraft model: the integral model**

With the development of new very flexible aircraft, together with the introduction of active flexible mode control into the flight control system of Airbus aircraft, AM-Airbus felt the need for pushing further the development of a new multidisciplinary modelization of the flexible aircraft.

Models (4) present a first level modelization of the flight mechanics; however this representation is not suitable for a complete simulation in the whole flight envelope, as it is only a simplified, linearized model. Moreover, the approach (2) assumes no dynamic couplings between flight mechanics and structural dynamics modes, an hypothesis that is endangered with new very large aircraft that exhibits a reduced frequency separation between flight mechanics and first with flexible modes, whereas approach (1) raises the community problems mentioned above.

To pass through these limitations Aérospatiale developed an integrated model that joined together the best representative models in aeroelasticity and flight mechanics. This model is also upgraded by a load model, as the load analysis process showed a strong dependency with flight mechanics, flight control system, and structural dynamics fields. The flight mechanics model is identical to the ones used in flight simulators, and is therefore valid for simulations in the whole flight envelope. The structural dynamics model is derived from the state space aeroelastic model (3); a specific Mach number and speed interpolation procedure has been incorporated to match its behaviour with the actual flight condition. Coupling equations between flight mechanics and structural dynamics are added for a proper description of the first flexible mode responses. The load model runs a monitoring of about fifteen loads of special interest, during all of the simulation:

$$\left.\begin{array}{l} \{\dot{X}\} = f(X, U, \text{ flexible behaviour}) \\ \text{Flight mechanics model} \\ \{\dot{X}_{flexible}\} = \begin{array}{l} [A(Mach, speed)] \cdot \{X_{flexible}\} \\ + [B(Mach, speed)] \cdot \{U, \text{ rigid behaviour}\} \end{array} \\ \text{Aeroelastic model} \\ \{loads\} = f'(X, U) \quad \text{Loads model} \end{array}\right\} \begin{array}{l} (5) \\ \text{intégral} \\ \text{model} \end{array}$$

This interdisciplinary model is named "the integral model", and is dedicated to the flight control system validation. It can be run in differed time on a desk simulator, as well as on real time on a development simulator, with a realistic cockpit environment.

• **The other way in aeroelastic modelling : CFD / FEM time domain coupling**

The evolutions of flexible aircraft modelizations described above were mostly required by the implementation of the EFCS. Aside from these motivations is now growing the simulation in the time domain of a CFD code together with the dynamic finite element model of the structure. The objective of such procedures is to make aeroelastic analyses inherit the progress of last transonic, unsteady aerodynamic codes.

$$\left.\begin{array}{l} [M]\{\ddot{X}\} + [B]\{\dot{X}\} + [K]\{X\} = Faero \\ Faero = fn(X) \end{array}\right\} \quad (6)$$

These new modelizations offer promising progresses in the flutter analyses of large transport aircraft flying in the transonic regime. However, such modelizations require high computationnal capabilities and are today only dedicated to some flutter analyses at high mach number. However, some results of these time domain analyses are incoporated in a linearized form in the aeroelastic models already mentioned.

Summary of flexible aircraft modelizations Capabilities

Analysis \ Model	(1) Flutter equations in the frequency domain	(2) Flutter equations with input / output definitions	(3) Structural dynamics in the State Space form
Aeroelastic Stability	X	X	X
Aeroservoelastic stability		X	X
Active mode Control law design			X
Integrated control law design			
Flight control system validation			
Flight test comparison capabilities	F / α	F / α ,TF	F / α , TF, f(t)

Analysis \ Model	(4) Structural dynamics +Flight mechanics State Space form	(5) Integral model Non linear flight mechanics + structural dynamics	(6) CFD / FEM Time domain coupling
Aeroelastic Stability	X		X (with non linear aero)
Aeroservoelastic stability	X		
Active mode Control law design	X		
Integrated control law design	X		
Flight control system validation		X	
Flight test comparison capabilities	F / α , TF, f(t)	f(t), whole flight envelope	f(t) (including unsteady aero measurements)

F / α   frequency/damping
TF   Transfer functions
f(t)   accelerometers time domain response

Evolution of FCS design and validation process

The evolution of the process has been pushed by two major reasons :
- the need to reduce the FCS design and validation cycles,
- the need to have an early and right assessment of adverse risks due to flexibility (ICAS, APC, OFL...).

We show below that AM-Airbus has prepared this evolution of FCS design and validation process simultaneously with the development, the issue of new flexible aircraft models and the merge of skills.

As long as the FCS design problems related to flexibility were not crucial, the FCS specialists used a linearized flight mechanics model in order to design flight control laws. The control laws were defined on the basis of classical or optimal control techniques.

The state space form of the flight mechanics model being easy to derive from the full non linear flight mechanics model, it was quite natural for FCS specialists to use the optimal control techniques.

Even if the problems described above were not a major concern on Airbus A320, it was necessary to check the absence of ICAS, to compute the OFL and to assess the effect of GLA (Gust Load Alleviation embedded in the FCS) on gust dynamic loads. For A320, most of the FCS validation work induced by the interacting systems and structure problems was made a posteriori after the FCS was defined. This a posteriori analysis was sufficient, because many problems had been anticipated and solved thanks to simple design precautions (e. g., low pass filtering of structural modes). At this time, the inhibition of structural modes responses was the policy of FCS designers.

But, when the aircraft become more and more flexible-it was the case of Airbus A330 and A340 - the classical process becomes too risky and too long.

A right in time and satisfactory design is very difficult to obtain if FCS is designed only on the basis of the flight mechanics model.

The evolution of the process comes along with the state space form of the aeroelastic model.and with the need to anticipate design problems coming from the presence of structural modes close the flight mechanics modes.

In the research field, this formulation has been widely used since the late seventies.

At AM-AIRBUS, these models were used later, typically in the mid eighties, but, first limited to aeroelasticity applications.

The development of Airbus A340 family gave the opportunity to distribute the aeroelastic model to FCS designers and to share more and more the skills involved in FCS design and validation (FCS, loads and aeroelasticity specialists). The model (4) approach 2 is now used for FCS design.

To distribute this model is preferred to the exchange of transfer functions often used for military aircraft FCS design, because the model (4) is adequate for a direct application of all recent optimal control techniques.

Other advantages in using model (4) for FCS design are listed below :
- the possibility to combine several design criteria, not limited to handling, but including structural loads and dynamics criteria,
- ICAS and APC can be monitored,
- optimisation of sensors position is easily achievable.

It means that handling objectives of the control can be worked out with structural dynamics objectives, including an active control of flexible structural modes (Ref 6). These objectives can be met while reducing the number of iterations between FCS, loads and aeroelasticity specialists.

However, because of some simplifications which were made to build model (4) approach 2, - e.g., no dynamic coupling between flight mechanics and structural dynamics modes, use of a limited number of modes -, it remains necessary to perform validation of the FCS design with more complete models and with tests.

Before the flight test, the current practice is the validation of the FCS design with the complete flight mechanics, complete loads and aeroelastic models. Typically, model (2) is used for aeroelasticity, model (4) approach 1 for loads analysis and the complete non linear mechanics model for handling qualities analysis.
The validation process with the complete models is long. If some problems are found with the complete models- for example, loads increase which cannot be sustained by the structure- , it can be too late to find a solution which would avoid structural reinforcements. Therefore, it is necessary to improve the validation process in order to anticipate and find, earlier than before, solutions to problems which can happen in relation with structural flexibility and FCS design (Ref. 5).
A way to anticipate better such problems is to extensively use the integral model (5). Even if the integral model cannot replace the individual specialized models, it is the best model for flight mechanics simulation of a flexible aircraft and for quick design validation purpose. With the possibility to survey structural dynamic responses as well as loads, the integral model offers capabilities for FCS design analysis in relation with questions raised by structural flexibility (including loads).

Finally, flight test results are used to consolidate theoretical analysis and validation activities. We show below how the flight tests can support FCS design and validation process.

Flight test identification of the structural dynamics and its use for EFCS design and validation

Previous paragraphs have presented the increasing use of models for control law design of today's high flexible transport aircraft. The complexity of the modelizations have grown up to respond to the new issues raised by integrated flight mechanics − flexible mode control systems.
These new flight control systems push the flight tests in a similar way. The main objectives of flight testing are more or less unchanged from the early years of first flight control system development : aircraft security demonstration, analyses of control system performances, data recording for model validation and adjustement. However, these three activities have known recently many evolutions linked to the specific flexible aircraft flight control laws.

With the Airbus A320 was first introduced EFCS in a civil aircraft. Even if the flight control law of this aircraft is not dedicated to flexible mode control, the in-flight flutter clearance demonstration had to take into account the new specificities of the "aeroservoelasticity". The influences of the flight control law on the dampings of the flexible modes had to be measured during the flight tests. Another consequence is that the transfer functions characteristics (aircraft response / control surface order) of the aircraft became of first interest for flutter clearance, and a major point for aeroservoelastic model validation, in addition to the usual frequency / damping characteristics (Ref. 3).

Introduction of an active flexible mode control function, (passenger comfort improvement on Airbus A340-A330) brought a second evolution in flight testing. Flutter flight tests results took place not only in the control law validation process, but were used for control law adjustement. Aircraft transfer functions of interest for control law tuning were measured, using control surface sine sweep excitations usuallly used for flutter flights. Although the aeroelastic model behaviour was very close to the aircraft , some refinements of the flexible mode control law were performed using these transfer functions. Later flights were then dedicated to comfort law performance and stability margins demonstration (Ref 4).

All of these new flight tests driven by new flight control systems should not hide the older in-flight identification of the flight mechanics that was still an important feature for these aircraft. These tests followed classic procedures : calibrated inputs on the control surfaces are applied to induce a proper excitation of the flight mechanic modes ; aircraft responses are recorded, and used in an identification procedure of the flight mechanics derivatives. The process is repeated for many flight conditions and excitation levels, providing an identification of the aerodynamic gradients, including

their non linearities, in the whole flight domain. From this data package a model of the aircraft flight mechanics is built that produces responses nearly identical to the one of the real aircraft. This model is the basis of the design of an efficient control of the rigid-body modes.

For the development of a streched version of the A340-300 (the A340-600/500) the flight test activities is going to evolve once again. The integration process between flight mechanics and structural dynamics discussed in the previous paragraphs in the modelization and control law synthesis fields will reach the flight testing . As a model of the flexible modes behaviour is necessary for the integrated control system design, the identification of this model during flight test will be performed and used for control law adjustement, as it is today's usual pratice for the rigid body mode. Moreover, this identification will be linked with the classic flight mechanics identification, to provide "integral identified models", describing both rigid-body and structural dynamics responses.

The identification of this model will be based on both usual rigid body excitations and sine-sweep excitations for flexible modes . The beginning frequency will be lower than the one used for flutter sweeps to provide information about the aircraft response in the overlap aera of flight mechanics and structural dynamics bandwith. The identification methodology used the output-error approach. Initialization of the flight mechanics parameters is taken from the theoretical model, weheras the flexible aircraft model is initialized by a combination of a least–square estimation of the impulse response, transformed into the state space form with the ERA procedure (Eigenspace Realization Algorithm). The output-error minimization process can then be carried out on a model of both rigid and flexible modes; influences of rigid-body modes at the structural modes frequency is therefore taken into account properly.

This identification provides the control law designers with the model required by the integrated flight mechanics and flexible modes control law approach selected by AM-Airbus for future large civil aircraft.

Conclusions

With the development of large transport aircraft, the structural dynamics issue is no more the field of dynamics loads and flutter specialists only. Control law design, flight control system validation, flight test identification are now activities where strong capabilities around the flexible aircraft questions are needed. Exchanges of modelizations, flight test results, and knowledge between the specialists of these different areas is a key point for the realization of the best flight control system on these aircraft.

References

(1) Roger, K.L, "*Airplane Math Modeling Methods for Active Control Design*", Structural Aspects of Active Control Design, AGARD-CP-228, Aug. 1977, pp. 4-1 to 4-11.

(2) Karpel, M., "*Physically weighted approximations of unsteady aerodynamic forces using the minimum – state method*", NASA TP3025, March 1991.

(3) Lacabanne M., Esquerre JP., "Correlation between Theoretical Flutter Models and Tests for Civil Aircraft", International Forum on Aeroelasticity and Structural Dynamics, June 1991, 91-133, pp. 594 to 602.

(4) Seyffarth K, , Lacabanne M., Koenig K., Cassan H., "*Comfort In Turbulence for a Large Civil Transport Aircraft*", International forum on aeroelasticity and structural dynamics, Strasbourg 1993.

(5) Besch, H.M., Giesseler, H.G., Schuller, J., "*Impact of Electronic Flight Control System Failure Cases on Structural Design Loads*", AGARD Report 815, Sept. 1996, pp. 14-1 to 14-10.

(6) Kubica, F, "*New flight control laws for large capacity aircraft experimentation on Airbus A340*", ICAS 1998.